UCRL-PROC-202959

The USHT-ITER Model Coil Program Achievements

R.J. Jayakumar, J.V. Minervini, J. Wohlwend, N. Martovetsky, R.J. Thomas

March 17, 2004

16th International Conference on Magnet Technology
Ponte Vedra, FL, United States
September 26, 1999 through October 2, 1999

Disclaimer

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

The USHT-ITER CS Model Coil Program Achievements

R. Jay Jayakumar(1), J.V. Minervini (3), J. Wohlwend(2), N. Martovetsky(1) and R.J. Thome(3)

Abstract--The International Thermonuclear Experimental Reactor (ITER) collaboration has fabricated an 18 layer CS Model Coil (CSMC) designed for producing a 13 T peak field at an operating current of 46 kA. A vertical preload structure applies up to 20 MPa on the coil. The US Home Team has designed and fabricated the 10 layer (2 in hand) inner module of the CSMC which consists of 4 layers of high field conductor and 6 layers of moderate field conductor. Each band of a layer was wound, then corkscrewed to form a two in hand layer. Compound bends on the leads were formed to provide for joints, tension plates which support the lead loads were welded to the conductor, terminations for the interlayer (layer to busbar) joints were added and the conductor was heat treated. The turns were insulated and then layers assembled with additional insulation to form the precise geometry, the coil was vacuum epoxy impregnated in a mold and the joints were assembled and insulated. The base structure, the upper support structure, superconducting busbars and the He plumbing for the inner module were also fabricated. All these subsystems were shipped to JAERI, Naka, Japan for installation which is complete and cooldown is in progress. The completion of this large, unprecedented and state of art pulsed superconducting magnet will provide the basis for many future developments in large superconducting magnet design and fabrication.

I. INTRODUCTION

The US Home Team was responsible for the design and fabrication of the inner module, the busbars and the support structure for the ITER Central Solenoid Model Coil [1]. The 45 tonne inner module (790 mm ID, 1355 mm OD, 1775 mm high winding with additional 500 mm high buffer zone on each end), consisting of 10 layers made with two different conductor sizes and 5 different strands, will generate 13 T at 46 kA and is capable of simulating the ITER CS scenario with a ramp rate of up to 1.2 T/s. The essential design concept and several tooling and process descriptions were reported in previous publications [2-4]. This paper reports further fabrication details and gives an overview of the inspection of parts and the assembly and accomplishments.

II. INNER MODULE FABRICATION RESULTS

A. Overview of The Inner Module Fabrication

The inner module was fabricated from a Cable-in-Conduit-Conductor (CICC) made from a 6 stage superconducting cable inserted in an Incoloy908® jacket and compacted. The cables for inner 4 layers was supplied by the EU team, the next 4 layers by US and the outermost 2 layers by JA team.

Manuscript received September 27, 1999. This work was supported by Department of Energy, Office of Fusion Energy Sciences.

1. *Lawrence Livermore National Lab, Livermore, CA, USA*
2. *General Atomic, San Diego, CA, USA.*
3. *Massachusetts Institute of Technology, Cambridge, MA, USA*

The two-in-hand conductor was wound and leads were formed and lead support plates were added in the Lockheed-Martin (LM) facility in San Diego, and lead terminations were added and coil was prepared for heat treatment in an MIT facility near Boston. The coil was heat treated in a large vacuum furnace in Ohio and the turns were insulated in the MIT facility. Then the layers were returned to the LM facility where the innermost layers were compressed over a mandrel and the other layers were compressed over the layer insulated inner ones. Lead support parts were assembled together as the layers were added and the large assembly was vacuum impregnated in a single charge of the epoxy. The lead terminations were assembled into joints and outer boxes were welded and joint insulation boxes were added. The assembled inner module is shown in Fig. 1.

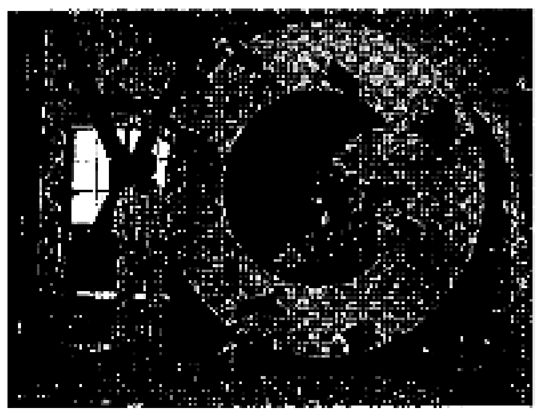

Fig. 1 Inner Module before shipment to the test site

The following description gives the general results of these processes with special emphasis on heat treatment and coil impregnation. Layers 1 through 4 are designated 1.1 to 1.4 and layers 5 through 10 are designated layers 2.1 to 2.6.

B. Coil Winding, corkscrewing and Lead Forming

The winding radii of the coil needed to be somewhat (~10mm) larger than the final radius. The length of the layer bands was accurately controlled so that the leads would end up at the appropriate angular locations in the assembly and some variation in radius was permitted. The average winding radii were within a few mm of the target, but the variation between turns was about 10 mm for most layers and was upto 20 mm for the layer 7. The corkscrewing tool made the turns circular and the layer axis could be accurately established to align the lead orientation and geometry in the 3 dimensions. Ultimately, all leads were fabricated to within 2 mm of the desired geometry as confirmed by templates.

C. Tension plates

The lead support tension plates made from Incoloy plates (slightly less in thickness than the conductor width) were profile machined on 3 axis machines with an ASME code weld prep with two legs for root welds. The space between the root weld legs was purged with argon to prevent Stress Accelerated Grain Boundary Oxidation (SAGBO) [5] and after the root welding the sloping edges were filled with Incoloy weld metal. The roots and welds were inspected for cracks and ground and rewelded if they were found. After initial problems on welding and inspection were resolved, all the tension plate welds satisfied ASME inspection criteria.

D. Lead Termination

The Glidcop lead terminations were added by stripping the jacket off the cable by accurate machining and splitting the jacket, removing the chromium plating from the strands and then compacting the Glidcop tube over the cable. The Glidcop terminations had an end Monel piece gold brazed to the Glidcop and this braze has to withstand loads during compaction and operation and therefore these brazes were inspected for Japanese Gas Law requirements by X-ray, ultrasonic and pressure and leak tests. The finished terminations had to be precise to within 1 mm (transverse) to enable the assembly of the joint. However because the compaction process increases the length of the jacket, the length of the termination could be controlled only to within about 6mm. Table I shows the geometry variation in the terminations.

Table I
Lead Terminations Dimension Measurements

Total length from He connector	650.8+/-4.7 mm
Length of uncompacted region +Monel	165.1+/-6.5 mm
Glidcop OD CS1 leads	42.1+/-0.12 mm
Glicop OD CS2 leads	41.6+/-0.07 mm

E. Shotpeening and Heat Treatment

The Incoloy surface is mostly under compression due to compaction, but the winding operation and lead forming leaves significant residual tensile stresses. Under these conditions, the Incoloy is susceptible to cracking by SAGBO during heat treatment and to prevent it, the layers are first shot peened with S-110 steel (MIL 13165C) shots. The intensity and coverage were first calibrated by the bowing of Almen strips (0.018 to 0.025 mm) mounted on the faces of the conductor. The coverage is saturated if the the intensity at 900 mm per min rate is 90% of the intensity at 450 mm per min. In all cases, the layer shot peening tests gave close to the higher values of intensity. 12 nozzles were used and the pointing was adjusted for different radii of the coil.

The layers were heat treated individually or as double layers on the basis of schedule needs. Analysis was confirmed in practice that even for double layers the temperature difference between various regions was within 15° C during ramp ups. The layers were heat treated in a large vacuum furnace with a vacuum of better than 1x 10^{-4} Torr. In addition, the cable space in the jacket was purged with ultrapure argon so that the exhaust had less than 0.3 ppm of oxygen and 1 ppm of water. The purge arrangement was complicated by the coaxial arrangement of purging to prevent termination fabrication residues from blowing into the cable space and the two hands of the layer and the additional need for purging the empty space under the tension plates on the leads. These specifications were enforced when the temperature was higher than 480° C. The temperature ramp program (specified by the strand manufacturers) was restricted by two additional considerations: The rate of ramp was limited by the inertia of the furnace and temperature uniformity across the coil,- typically the ramp rate was limited to 5-6° C /hr. Secondly, the presence of water vapor and oil residues (from strand plating and cabling) required additional long dwells up to 144 hours at 460° C. Testing of strands with these revised ramps showed that the critical current density remained unaffected. This careful purging of the conductor prior to reaching SAGBO temperature marks a critical aspect of the successful QA program.

Two sets of witness samples were prepared- one set was sample of Glidcop termination on cable for determining the sintering of the cable to the Glidcop surface and the other sets were critical current samples of the pertinent samples. The termination samples showed excellent bonding between the cable and jacket and the critical current of the witness samples [6] were satisfactorily close to reference sample measurements. Table II shows the summary of critical current measurements for the inner layer VAC strand.

Table II
Example of Conductor performance for different layers.

Samples	Critical Current (A) @ 12 T*	n value	Hysterisis loss +/-3T (mJ/cc)
CS1.1	118.2	33.1	111.5
CS1.2 &1.4	117.7	32.8	109.1
CS1.3 &2.1	117.4	32.3	110.6
Reference	115.5	32.3	102.8

*Heat treatment cycle - 185 C /20hr, 350 C/ 3hr, 460 C /144hr, 570 C /220hr, 650 C/175 hr. All ramps at 6 C /hr and ramp down at 25 C/hr.

Similarly the IGC wire coreacted samples for the layers 2.1 to 2.4, the Furukawa wire for layer 9 and Mitsubishi wire for layer 10 performed equal or better than reference samples and all of them met the ITER strand specifications. The heat treatment cycles for different layers were different . The layer 3 and layer 5 with different strands were coreacted with the VAC strand cycle and the suitability of this heat treatment for the IGC wire of layer 5 was checked in advance. In addition, busbars made with IGC wires were heat treated with the Furukawa and Mitsubishi strand layers and again the IGC strands performed very well.

A major achievement of this heat treatment program was the uneventful SAGBO-free heat treatment of Incoloy 908® jacketed conductors. With the appropriate quality in place, no SAGBO was ever observed even in the highly stressed location of the leads. For the inner module, approximately 2000 m (~25 tonne) of the conductor was heat treated (another 2700 m length was heat treated for the outer module in Japan). Detailed inspection of the outside and sectioned dye penetrant inspection of several meters of the cable space and the leads showed no evidence of SAGBO demonstrating the success of the heat treatment approach. Since Incoloy 908® is crucial to obtaining high current densities in Nb3Sn CICC conductors, this marks a major development in this field.

F. Shot blasting and Turn Insulating

The several hundred meters of coil layers which are also two in hand required automatic wrapping of the prepreg-Kapton-glass insulation. One of the major successes of the Model Coil R&D and production program was that this insulation was cured on the turns and inspected prior to final assembly. This ensured that insulation quality was not left to chance till the VPI of the coil was completed and the turn insulation quality could be guranteed, in advance.

The shot blasting to clean the coil surface was done on the same tooling as the shot peening. The insulating was carried out with 3 insulating heads while the coil was rotated on a rolling belt bed. The diameter of the insulating tape roll was limited by the space between the turns, which in turn is limited by the spreading of the turns to limit the conductor strain. A 0.2% strain was permitted and checked prior to insulating the turns. The variation of the coil radius caused additional problems due to inconsistent rotation of different turns resulting in tightening or opening of the turns and this caused some interruptions in the insulating process. The curing under pressure, carried out by a combination of wrapping tension and rubber component expansion under heating was very successful in obtaining uniform size of insulation. The heating during curing was accomplished by passing current through the turns. The overall variation in the cured insulation thickness (1.5mm) was less than 0.2 mm, although the total dimension of the conductor varied more because of the overwrapped glass. The leads and tension plates were insulated by hand application of the double prepreg-Kapton tapes and cured with a convection oven with the air circulating in a sealed volume around the leads and tension plates. The process was developed and tested in dummy trials. Although this was a time consuming operation, the process gave a reproducible and high quality product. All the turn insulation and the tension plates passed an inspection at 5kV DC applied by a brush.

G. Final Assembly of layers

There were several initial difficulties in this critical process which were resolved stage by stage. The method was to lower the larger layer onto its layer- insulated inner layer (the inner mandrel for the innermost layer) and then rolling it down to within the maximum allowable outer radius. This roll down required considerable force and the glass insulation was damaged. It was recognized that most of the load was due to the friction between adjacent turns and the process originally intended to push the turns together while compressing the turns. This axial compression was removed and in addition the weight of the turns above the pertinent turns was supported separately and these turns were allowed to rotate freely. After several process iterations the damage was minimized although not eliminated. The damaged portions of the glass was repaired by adding layers of glass. The simultaneous precise radial and azimuthal location of the

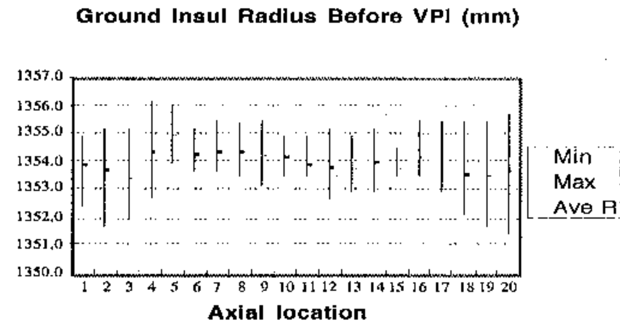

Fig. 2. Coil Outer radius at different axial locations (from bottom to top).

end of the turns (leads) was achieved by adjusting the layer insulation thickness and was quite successful.

One of the significant problems encountered in the program was an error in the coil length of layer 7B. This hand of the layer was too long by about 2 meters and the only way this could be resolved was by rotating the outer layers with respect to the inner layers, in a way such that the inner module relationship with the outer module remained the same. Fortunately this could be accomplished by additional holes in the tooling and changing the joint locations in the interface arrangement with no change to the outer module. The associated He plumbing also changed.

Table III
As built radii of the inner module layers

Layer #	Nominal Eng Radius mm	Average Actual Radius mm	Diviation +/- mm
1	854.7	855.0	2.3
2	913.5	914.7	2.3
3	972.9	970.2	3.0
4	1030.4	1029.7	1.3
5	1083.2	1083.6	2.8
6	1136.3	1136.4	1.5
7	1189.9	1189.5	1.0
8	1243.6	1243.1	2.0
9	1295.9	1295.1	1.5

All the terminations were aligned to within 2 mm in all directions. Copper current transfer saddle pieces were placed between the terminations and clamped together. Fig. 2 shows the final outer radius of the coil. (The target outer radius maximum is 1357 mm).

H. Vacuum Pressure Impregnation

The vacuum impregnation was one of the critical high risk steps in the process where proper penetration of epoxy without any voids and proper curing of the epoxy all over the coil is critically required for structural and electrical integrity. A 3 piece outer mandrel and a top lid were added and the joints were sealed with RTV. The top lid was then added. All the lead penetrations through the mold at the bottom and top had to be sealed by special sealing plates with double seals and the sealing RTV was injected with a carefully developed process which ensured that the seal material flowed and also withstood the pressure and vacuum requirements after the RTV is cured.

The impregnation process required heating the assembly to about 50 C under vacuum of about 130 Pa, injecting epoxy, raising to the gel tempearture of 90 C and then curing at about 140 C. Since the assembly was very large with many penetrations and both the inner and outer mandrels were made from joined segments, there was a finite risk of leakage to prevent good vacuum. To improve the vacuum, additional vacuum bags were placed between the mandrels and the coil and the intervening space separately pumped.

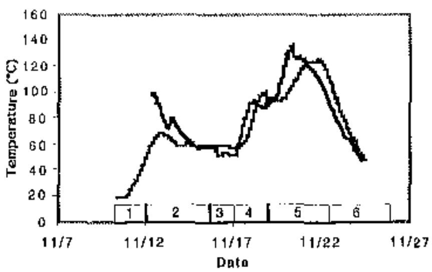

Fig. 3. Coil Temperatures during VPI. 1- Bakeout, 2-Hold, 3-Inject Epoxy, 4- Gel, 5-Cure and 6-Cooldown. The dark line corresponds to the average coil temperature and the gray line refers to the top buffer zone

The epoxy was prepared by separately deairing and heating the resin and the hardener and then mixing them in the specified ratio with a metering pump and injecting the mixture at the bottom of the mold. An injection port every 2 meter around the circumference of the coil was used for each interlayer space. Similarly at the top, the coil was pumped through a large number of ports

A sharply divided ramp and flat tops in temperature was not possible due to the inertia of the system and particularly the heating of the buffer zone (lead region enclosed by large G10 segments) was very slow due to low conductivity (see Figure 3). Because of the large thermal diffusion time of the components the outer mandrel, the inner mandrel, the bottom and top plates were each separately heated by electrical pads and the coil was heated electrically. The coil was divided into two opposing magnetic circuits to minimize inductance and magnetic field. In addition, bypass diodes were added across the terminals to minimize arcing and damage to terminations in case of electrical failure. Since the inner layers are well insulated, they tended to heat faster and cool slower. This created significant temperature gradients in the coil and the inner layers had to be cooled by a large flow of cold nitrogen gas. The temperature history of the inner layer (for example 5.5 refers to the average of layer 5 and 6) and the outer layers is shown in Fig. 4. The temperatures were calculated from resistance measurements. A vacuum of about 200 Pa was achieved. The actual epoxy used was about 1300 liters. The epoxy rose very uniformly and reached the top at the various ports almost simultaneously. This eliminated any worries about voids and flow backs from the top. The epoxy was milked a few times to eliminate any trapped air. Except for one instance of a local exothermic cure which was quickly corrected, the cure proceeded well and the final quality of impregnation as seen on the outside of the coil was excellent,

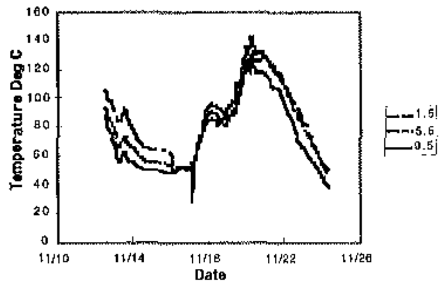

Fig.4. Distribution of coil temperatures during the VPI. The designations 1.5, 5.5 and9.5 refer to the fact that the temperatures were derived from the resistance of two adjacent layers- e.g. 5.5 refers to temperature derived from layer 5 and layer 6 resistances.

with no bubbles or voids. The lap joints were assembled by welding structural boxes and the outer prefabricated insulating boxes were added. The 19 joints were located within 0.2 deg in the azimuthal direction and within 1 cm of the required radius. The coil dimensional inspection, conductor flow measurements, hi-pot measurements were carried out and the module was shipped by ocean freight to Japan. The module has been installed in JAERI, Naka, Japan.

III OTHER ACCOMPLISHMENTS AND SUMMARY

In addition the 13 Tesla, 45 tonne, 10 layer inner module, the 70 tonne stainless steel support structure with the gravity and preload plates, legs, beams and tension rods were also fabricated and have been installed. 6 superconducting busbars were fabricated with precise geometries and special demountable lap joints and have also been installed. An intermodule bladder made with fiberglass composites was installed and the intermodular space filled with epoxy. The He plumbing for the inner module with pressure, temperature and flow sensors was also supplied to JAERI and has been installed.

In summary, the 10 layer, 13Tesla, 46 kA, 50 tonne inner module, the 70 tonne structure and the associated subassemblies for the CS Model Coil were successfully fabricated after an approximately 5 year design and fabrication program. All these fabricated items have met the ITER Model Coil requirements and the inner module has been installed in the Central Solenoid Model Coil Test Facility.

REFERENCES

[1] N. Mitchell et.al., "ITER CS Model Coil Project", *ICEC16/ICMC Conference, Kitakyushu, Japan*, May 20-24, 1996.

[2] R. J. Jayakumar et. al., "The ITER CS Model Coil Project", *Sixteenth IAEA Fusion Energy Conference, Montreal, Canada*, Oct 1996.

[23 R. Jayakumar et.al., "Fabrication of ITER Central Solenoid Model Coil Inner Module", IEEE trans. Applied Superconductivity, Vol. 7, pp.981 (June 1997)

[4] R. Jayakumar et. Al., "Design and Fabrication of the Inner Module of the CS Model Coil", *International Magnet Technology Conference, Beijing, China*, October 1997.

[5] F.M.G. Wong et. al., "Characterization of Incoloy 908 and avoidance of SAGBO during ITER Model Coil Fabrication", *13th Topical Meeting on Technology of Fusion Energy, Nashville, USA*, June 7-11,1998.

University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551